Stuart D. Bale – University of California, Berkeley
…for the THOR team (PI: Andris Vaivads, IRFU, Sweden)

Turbulence Heating ObserveR

thor.irfu.se

THOR Science

Exploring plasma heating and energization in space turbulence

- ✓ How is plasma heated and particles accelerated?
  - *Coherent structures & wave identification*
  - *Is plasma heating stochastic or coherent?*
- ✓ How is the dissipated energy partitioned?
  - *Electrons vs protons vs heavier ions*
  - *Heating vs. particle acceleration*
- ✓ How does dissipation operate in different regimes of turbulence?
  - *Pristine solar wind*
  - *Flow interaction regions*
  - *Shocks and sheath regions behind shocks*

First dedicated turbulence microphysics mission!

'FAST' for turbulence physics

Some history…

- ✓ **Cross-Scale** ESA Cosmic Vision proposal in 2007
  - 7 spacecraft constellation
  - NASA-funded Phase A participation
  - Solar Orbiter selected instead
- ✓ **EIDO*Scope*** ESA MoO with Japanese SCOPE in 2011
  - SCOPE not selected by JAXA
- ✓ **Tor** ESA S-class proposal in 2012
  - Shortlisted, not selected
- ✓ **Tor** Phase A study by SNSB in 2013
- ✓ **THOR** ESA M4 proposal in 2014
  - Selected for Phase 0/A study in June 2015 (34->10->3)

THOR timeline

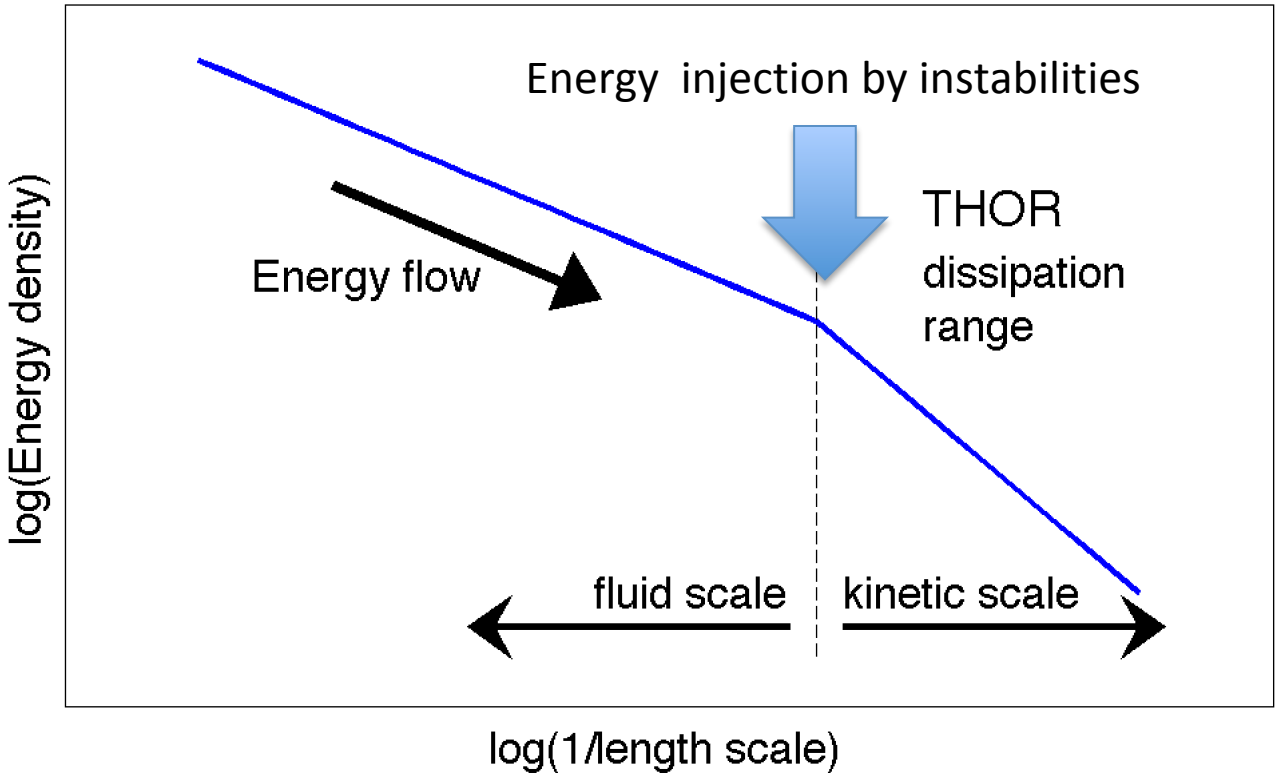
- ✓ 2015-01-15 Proposal submitted to ESA M4
- ✓ 2015-06-04 THOR selected for study phase
- ✓ 2015-06-11 kick-off of internal ESA Phase 0 study.
- ✓ 2015 fall End of Phase 0.
- ✓ 2016 -2017 Phase A study (w/ industry)
- ✓ 2016 THOR kick-off workshop
- ✓ 2017 spring Final down-selection (1 of 3)
- ✓ 2026 Launch

Relationship to 2013 Decadal

Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. Advances in understanding of solar and space physics require the capability to characterize fundamental physical processes that govern how energy and matter are transported. Such understanding is also needed to improve the capability to predict space weather.

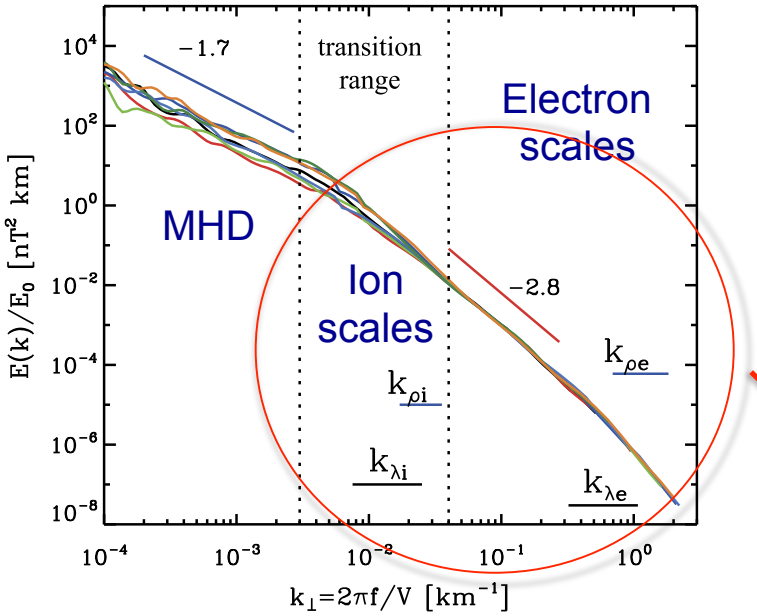
(some broader interest to astrophysics - electron heating in galaxy clusters, astrophysical shocks, accelerating systems, etc.)

Kinetic scales



Kinetic scales – magnetic field

Solar wind turbulent spectrum of magnetic fluctuations at MHD-Ion-Electron scales

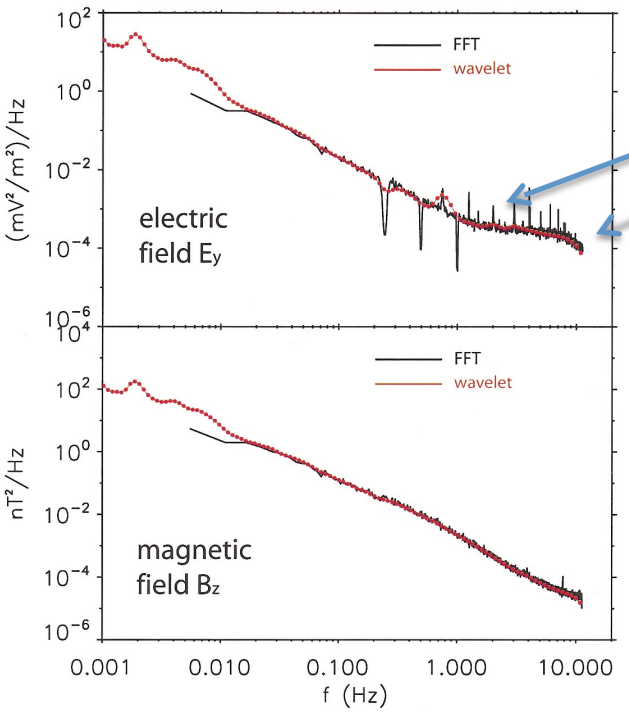


[Alexandrova, Chen, Sorriso-Valvo, Bale, Horbury, 2013 Space Science Rev.]

This corresponds to 10-1000 ms timescales

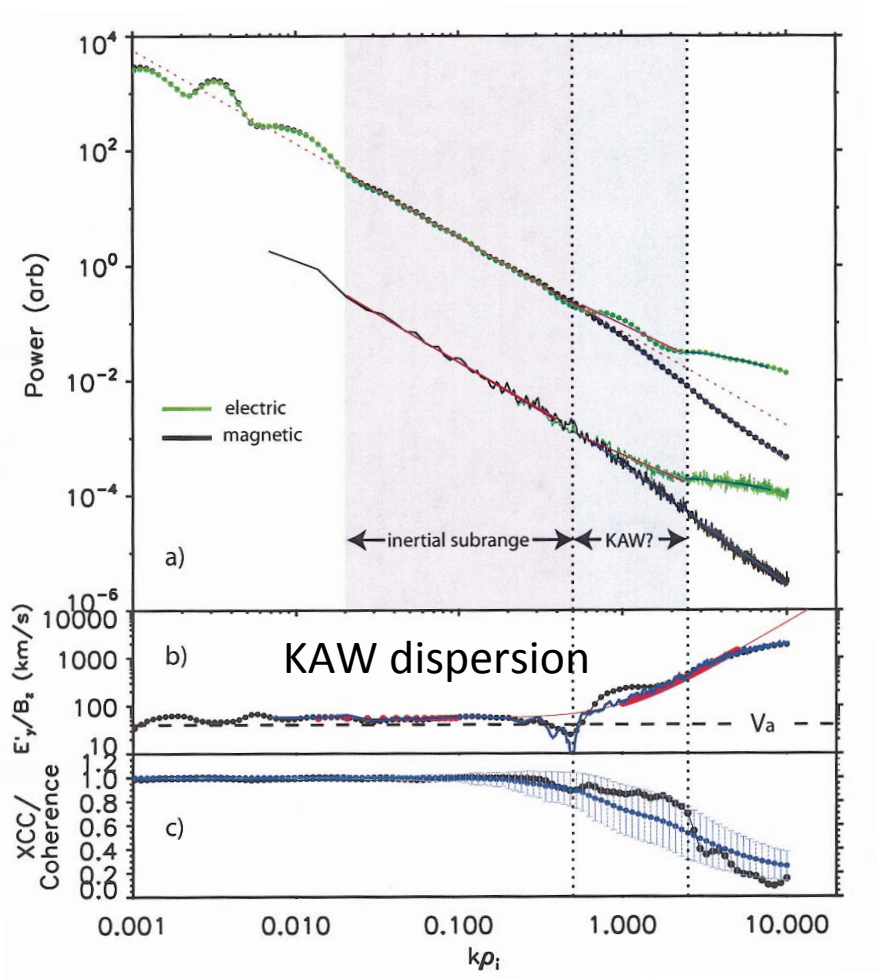
1. What is going on close to ion and electron scales?
2. Which plasma scale is responsible for the ion break?
3. Which plasma scale plays the role of the dissipation scale?
4. Physical mechanisms?
5. Nature of turbulent fluctuations : waves or strong turbulence?
6. …

Kinetic scales – electric field



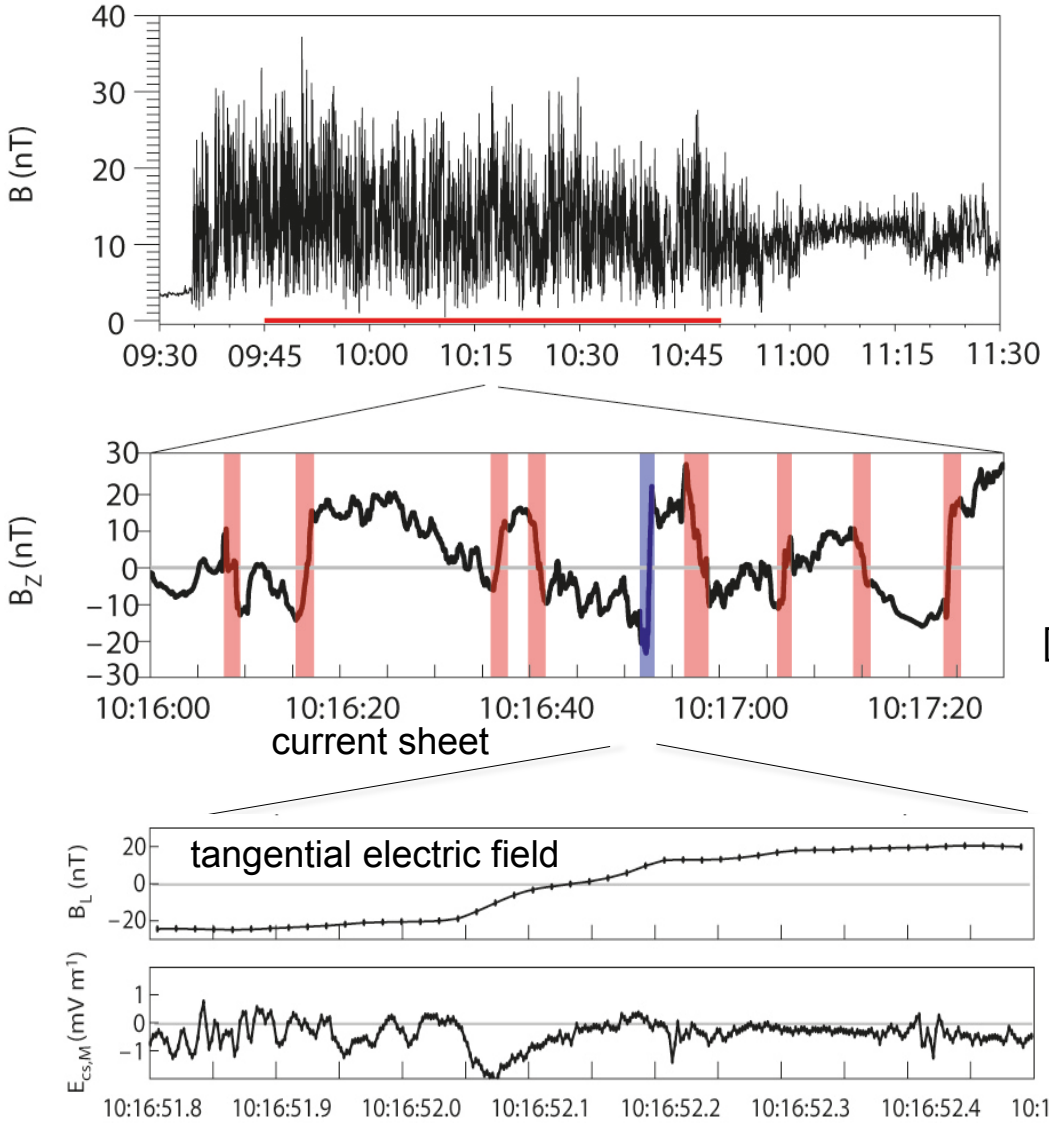
Spin tones
Instrument noise levels

Electric field measurements are a very powerful diagnostic, but difficult to make.



(Bale et al., 2005)

Coherent structures in situ data



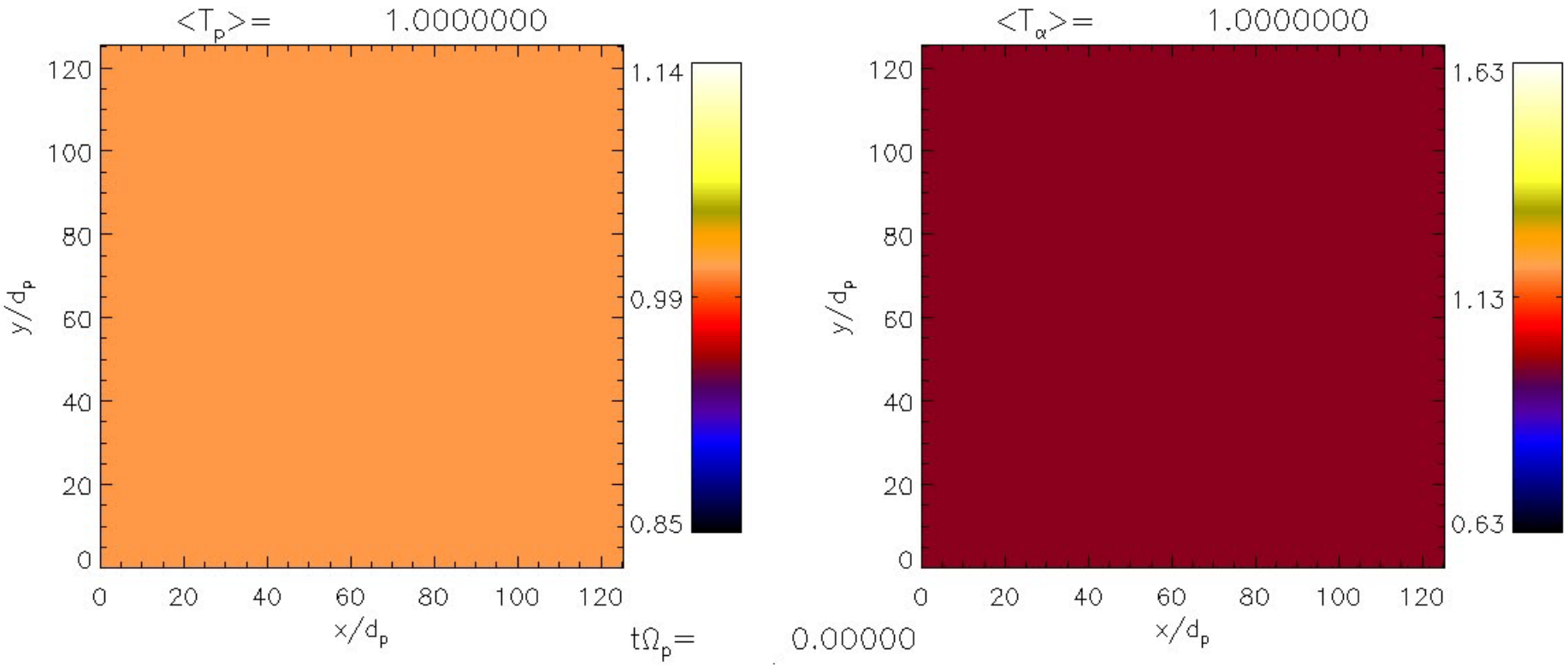
Kinetic scale current sheets observed within turbulence

[Retinò et al. , Nature Physics, 2007]

conversion from temporal to spatial scales from single spacecraft measurements

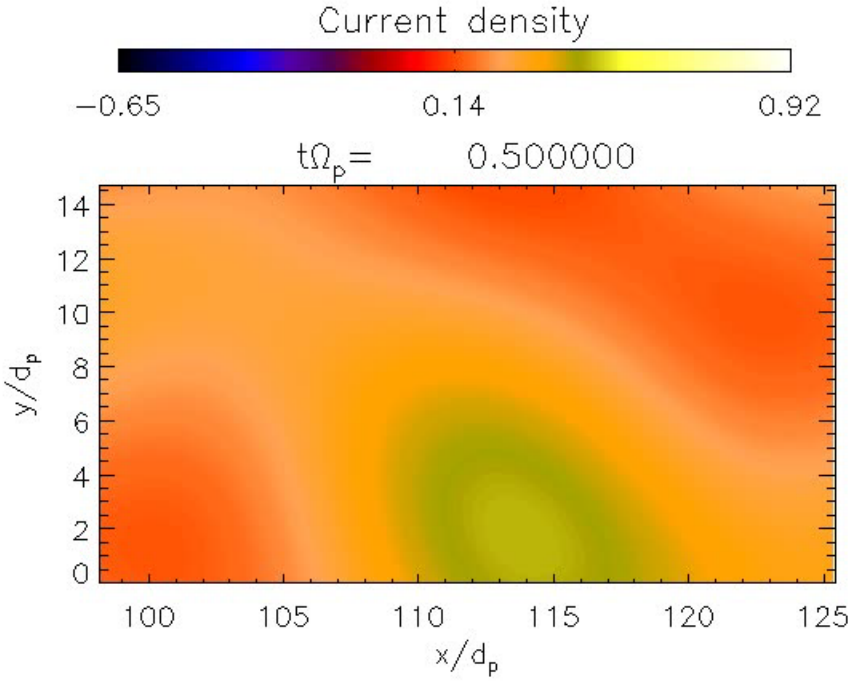
Existing particle measurements inadequate to quantify heating.

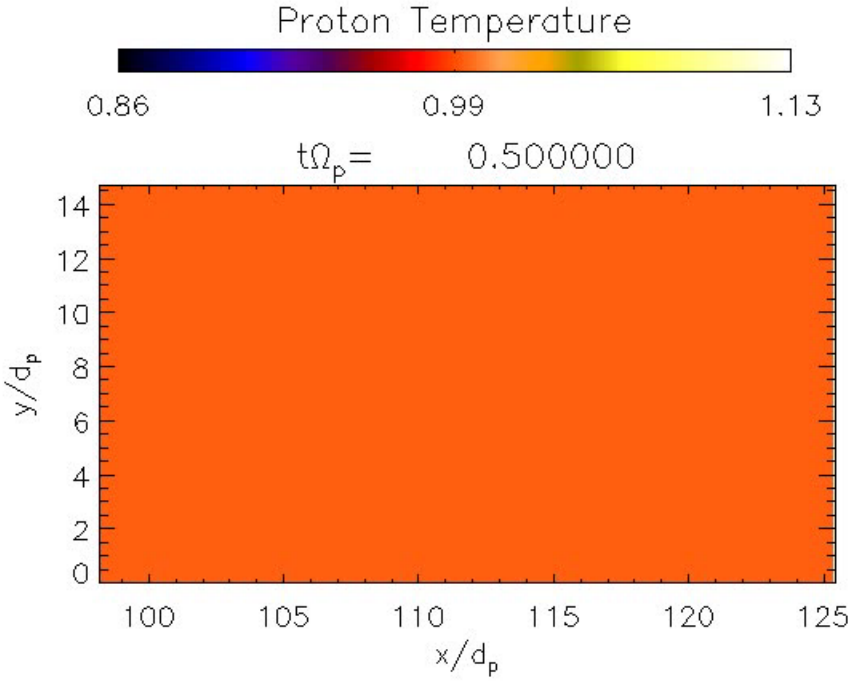
Heating in kinetic scale turbulence



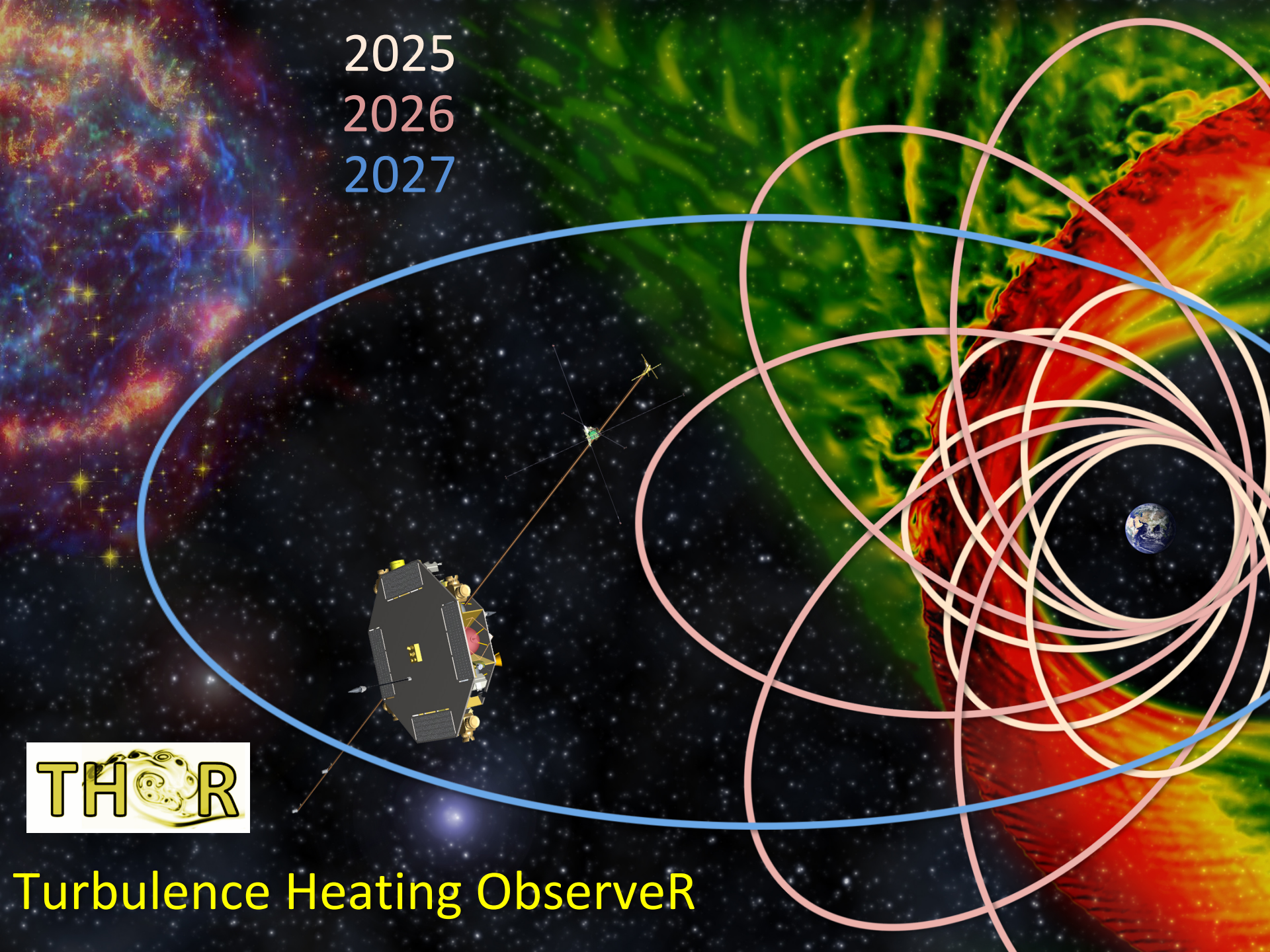
- ✓ different kinds of turbulent fluctuations contribute to heating (waves, coherent structures)
- ✓ heating is different among different ion species
- ✓ similar heating processes for electrons

Coherent structures - numerical simulations

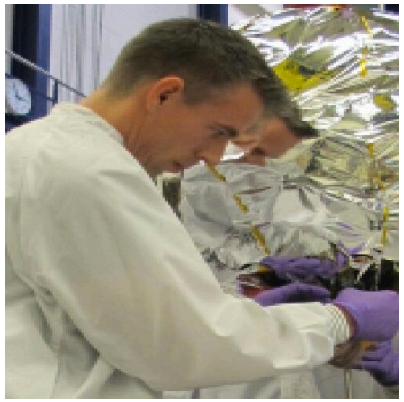




- ✓ Heating is localized in regions of strong current at kinetic scales.
- ✓ The structure is quasig-stationary over the time it would take a spacecraft to cross it.
- ✓ Phase velocity of structure can be estimated from single
- ✓ spacecraft measurements e.g. through conservation of E_{tang}.


2025
2026
2027
THOR
Turbulence Heating ObserveR

- Sun-pointer
- Slow spinner (2rpm)
- Sun-symmetry give advantages for electric fields and particle measurements



OHB SWEDEN

Mission profile

Eric Clacey
OHB Sweden

Mature payload

Table 7: *THOR science instrumentation.*

Instrument	Measured quantity	Range	Max. cadence	Requirements
MAG	Magnetic field	DC-50 Hz	128 sps	**RI-1**, **RI-2**, **RI-3**
SCM	Magnetic field	1Hz-200 kHz	524 ksps	**RI-1**, **RI-2**
EFI	Electric field Fast	DC-200 kHz	524 ksps	**RI-1**,**RI-2**,**RI-4**,**RI-7**
FAR	ion moments		32 sps	**RI-6**
FWP	Fields and waves		524 ksps	**RI-1**, **RI-7**
ESA	Electron distribution	1 eV–20 keV	5 ms	**RI-7**, **RI-9**, **RI-10**
IMS	Ion distribution	5 eV–32 keV	150 ms	**RI-5**,**RI-6**,**RI-8**,**RI-11**
CSW	Cold solar wind ions	5 eV–32 keV	150 ms	**RI-8**
EPE	Energetic particles	e^-: 20 keV–700 keV i^+: 20 keV–8 MeV	7.5 s	**RI-12**
PPU	Particle data products			**RI-6** to **RI-11**

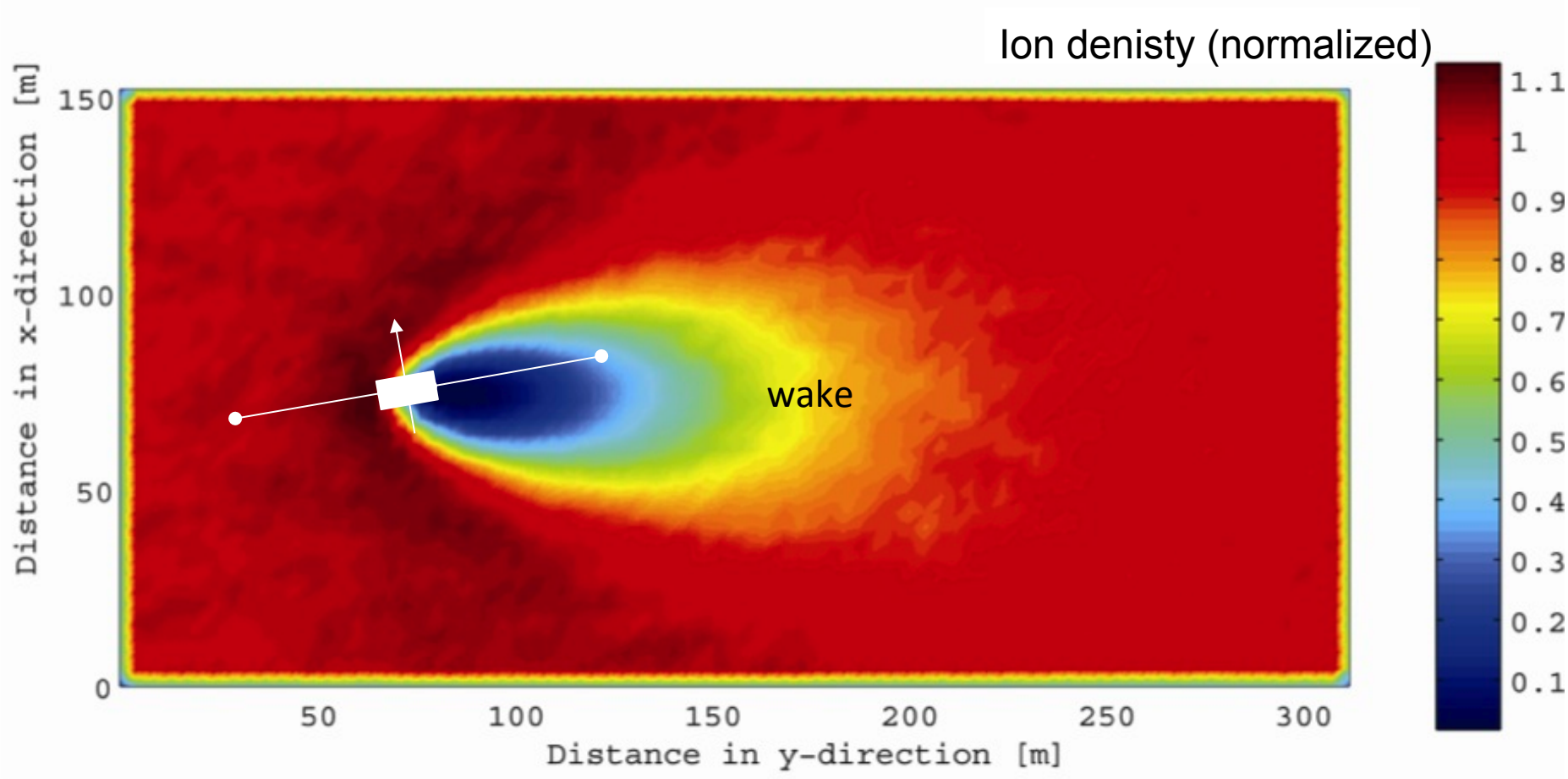
Single s/c with highest resolution field and particle measurements ever, to satisfy the THOR science requirements!

Mature payload

	Instrument	Measurement	Teams (PI, Co-PI, *Lead-Col*)
FIELDS	**MAG**	B field DC	IWF(AU), ICL(UK)
	SCM	B field AC	LPP(FR), LPC2E(FR)
	EFI	E field DC/AC	IRF(SE), UCB(USA), *SRC-PAS(PL), KTH(SE)*
	FWP	E&B data products	IAP(CZ), SRC-PAS(PL), *U.Sheffield(UK), LESIA(FR)*
PARTICLES	**ESA**	e^- spectrometer	MSSL(UK), NASA/GSFC(USA)
	CSW	Cold solar wind ions	IRAP(FR), BIRA-ISAB(BE)
	IMS	H^+, He^{++}, He^+ ,O^+	LPP(FR), UNH(USA), *ISA/JAXA(JP), MPS(DE)*
	PPU	Particle data products	INAF-IAPS(IT)
	FAR	Faraday cup	MFF(CZ)
	EPE	Energetic particles	IEAP(DE), U.Turku(FI)

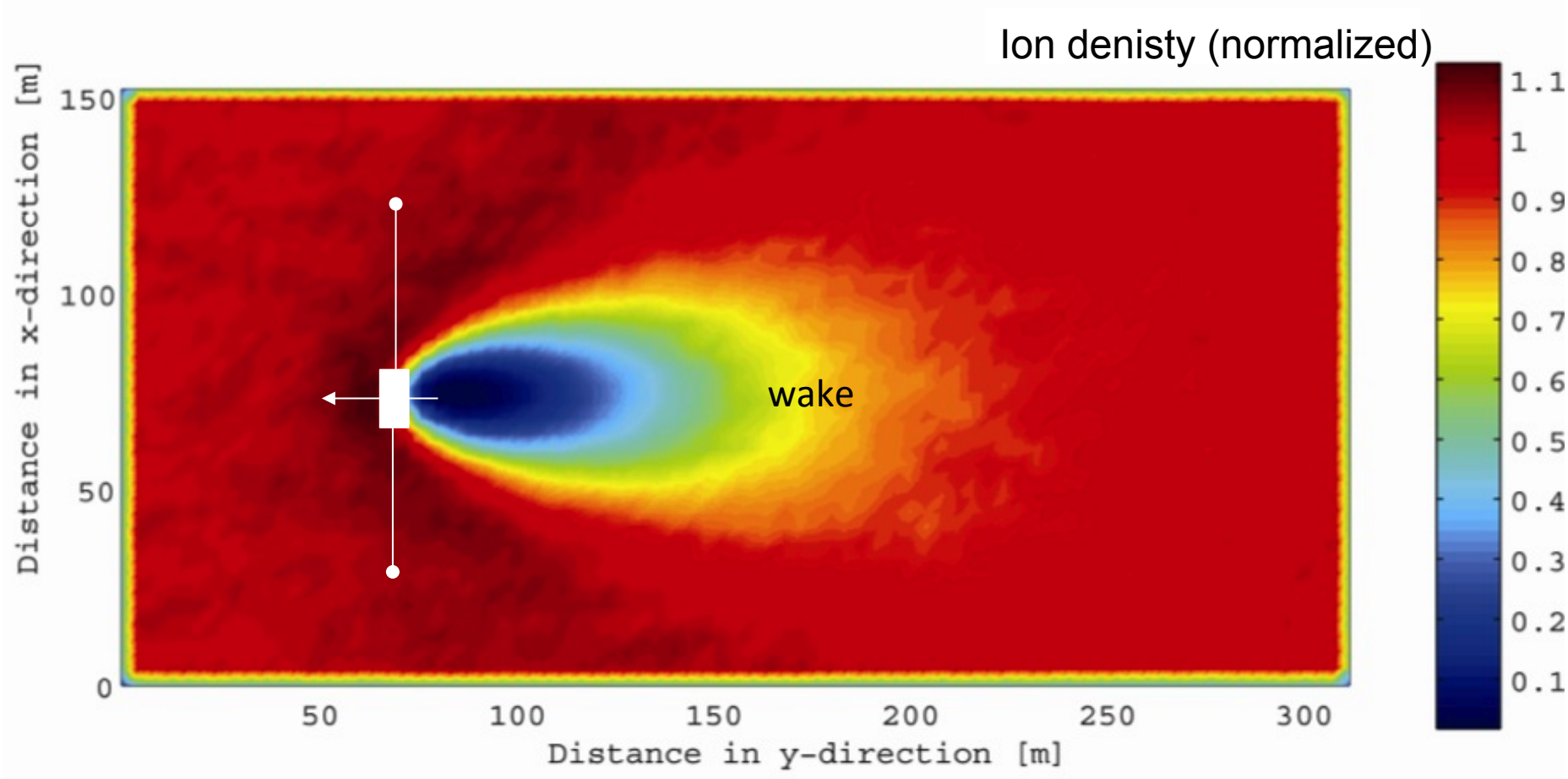
Single s/c with highest resolution field and particle measurements ever, to satisfy the THOR science requirements!

Electric field measurements



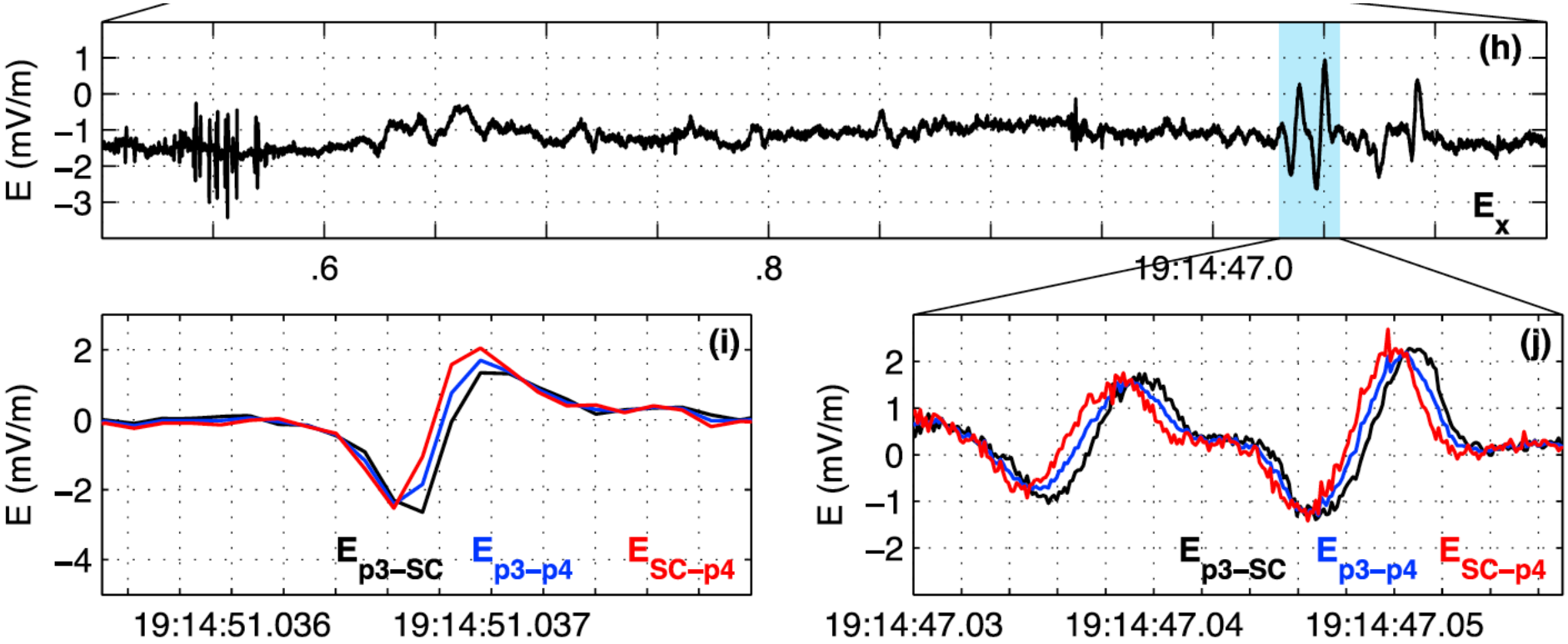
Spin plane close to ecliptic

Electric field measurements

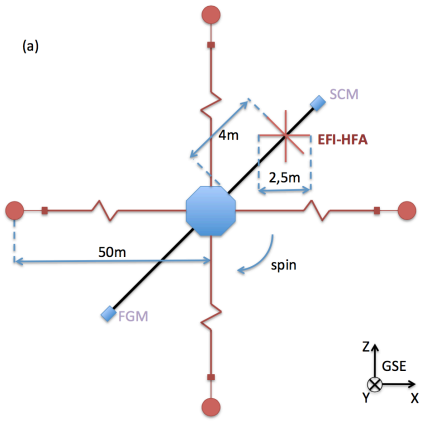


Spin axis towards Sun. This requires extra fuel (mission life-time shorter) but significantly increases the precision of E field mesurement.

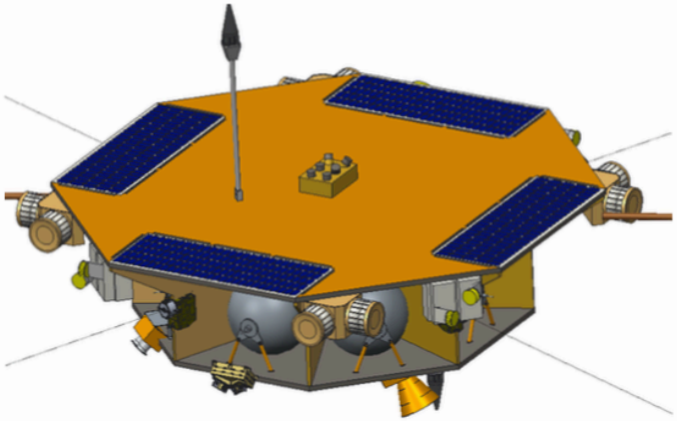
EFI interferometry II

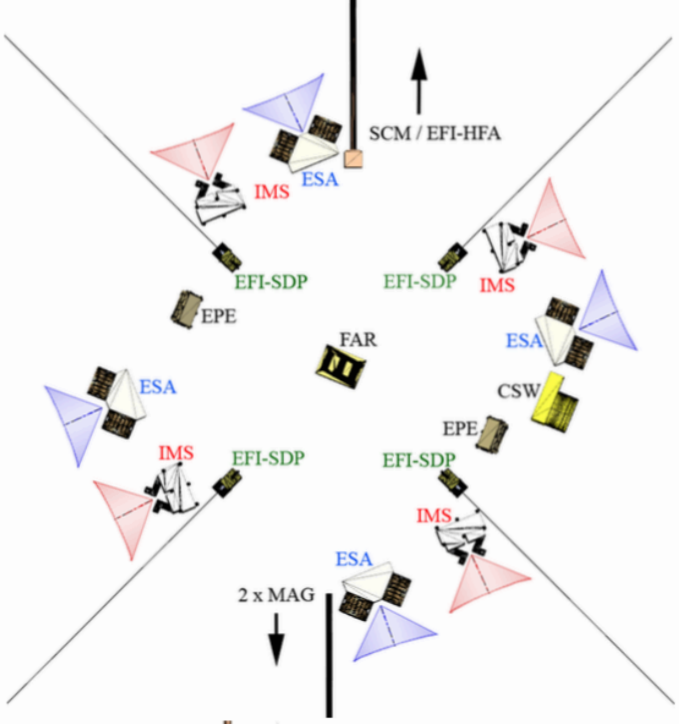


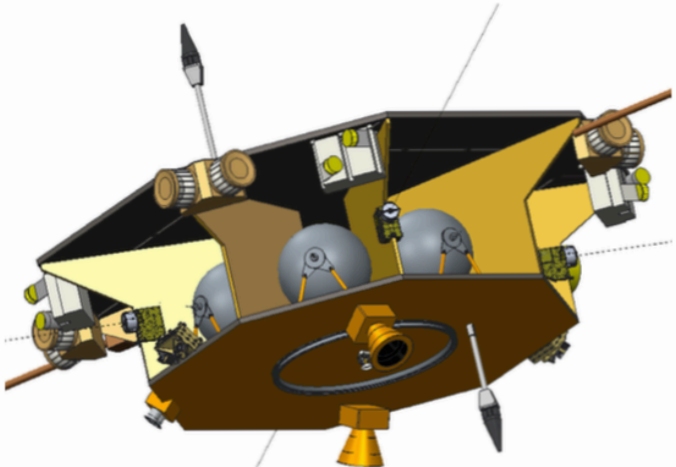
(Graham et al., 2015, GRL)

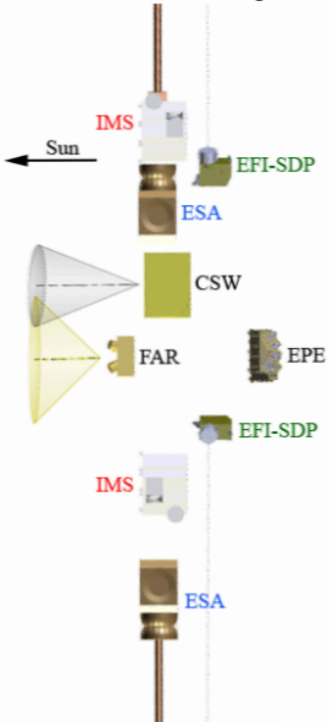


Electrostatic solitary waves with distinct phase speeds.

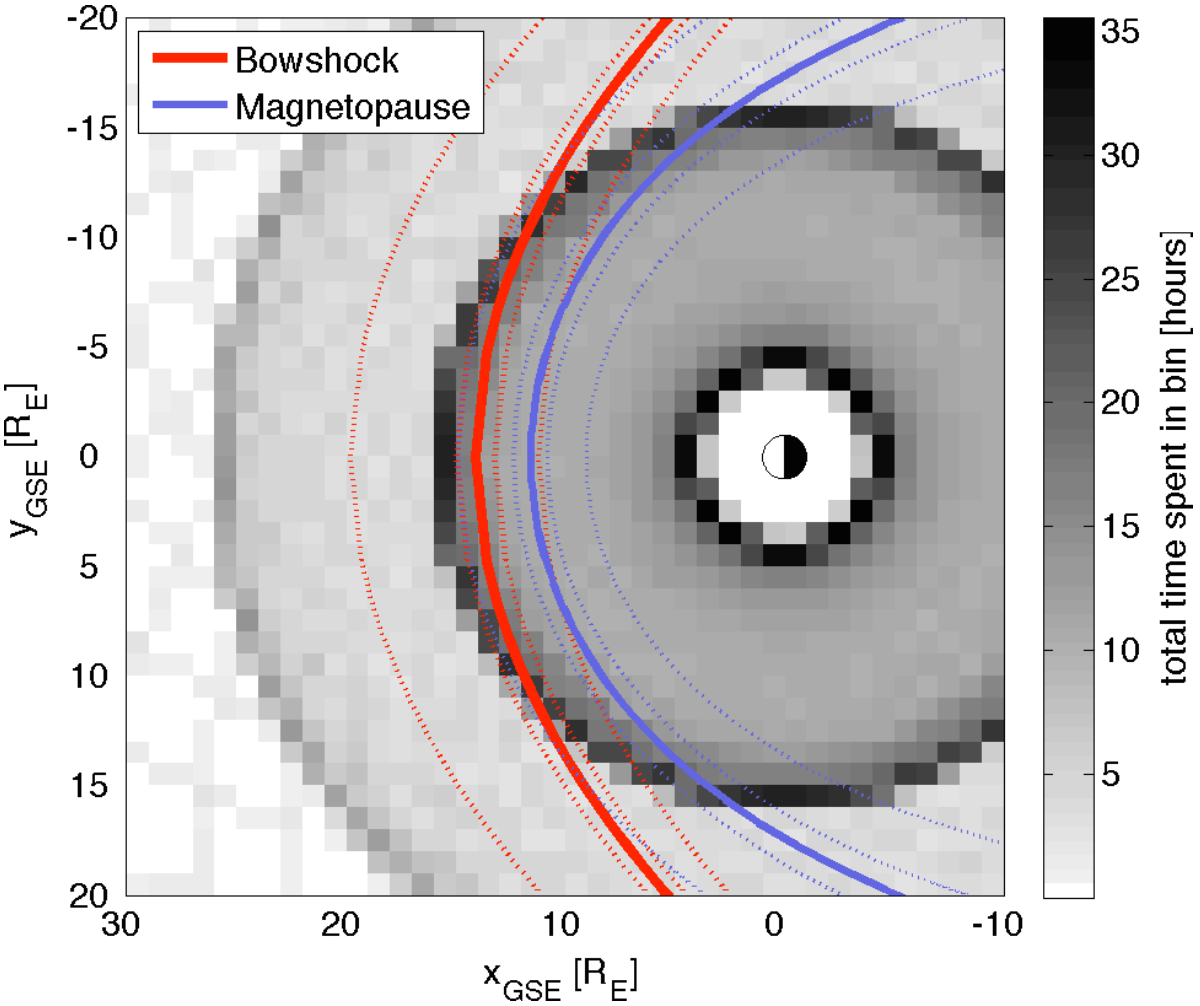



SCM / EFI-HFA
IMS
ESA
EFI-SDP
EFI-SDP
IMS
EPE
FAR
ESA
ESA
CSW
EPE
IMS
EFI-SDP
EFI-SDP
IMS
ESA
2 x MAG




IMS
Sun
EFI-SDP
ESA
CSW
FAR
EPE
EFI-SDP
IMS
ESA

Orbital coverage



- 3 year prime, 2 year extended, eventually to L1
- ESA is investigating Real Time capability for space weather

Survey and Burst modes

RM-3
10 days of data saved on-board.
Scientist in the loop (SITL)

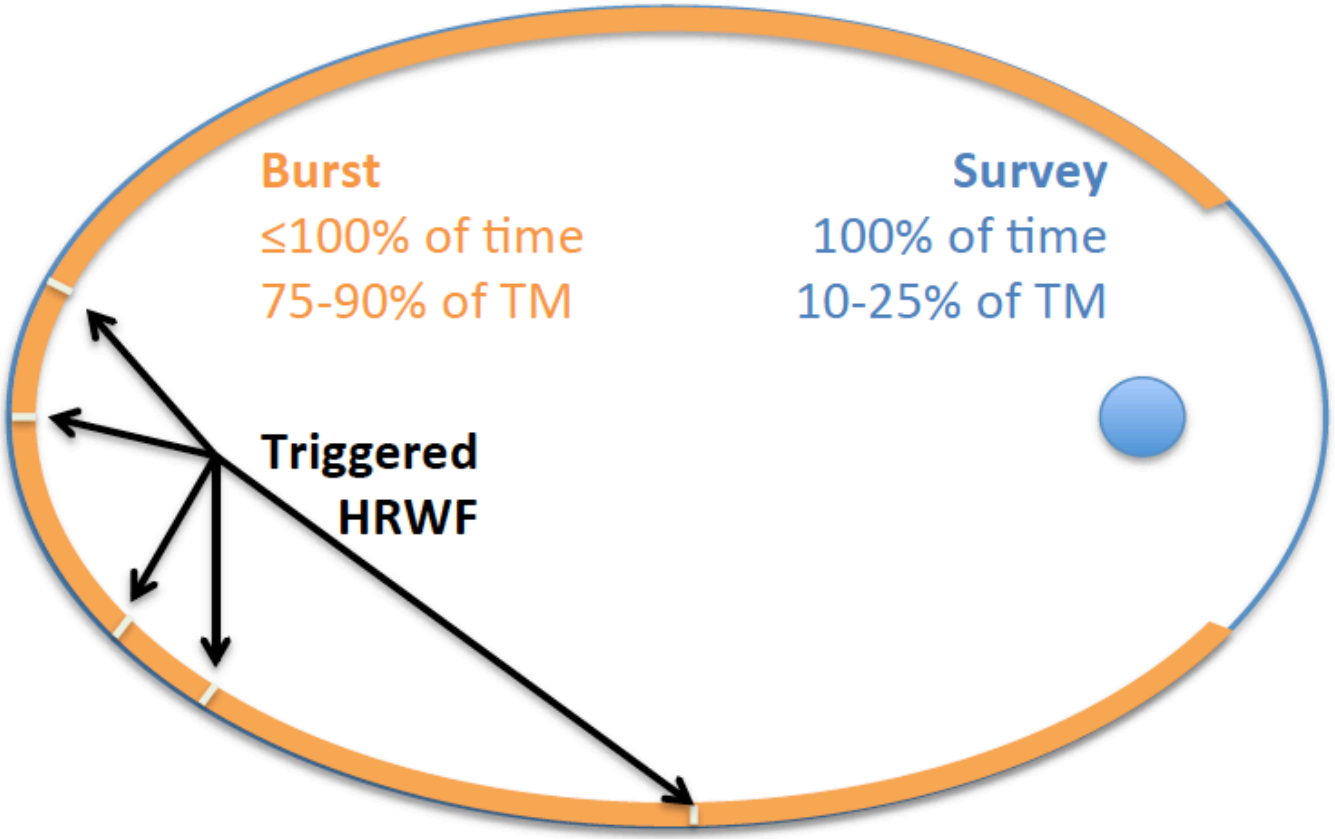


Figure 57: *THOR telemetry acquisition along the orbit. Survey data is sampled all the time, while Burst data is acquired only in the key science region. Burst data contains snapshots high-resolution waveforms (HRWF) of electric and magnetic fields; snapshot acquisition is both time and data triggered.*

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

December 17, 2014

Reply to Attn of: Science Mission Directorate

Dr. Alvaro Giménez
ESA Director of Science and Robotic Exploration
European Space Astronomy Centre
P.O. Box 78
28691 Villanueva de la Canada
Madrid, Spain
M4support@cosmos.esa.int

Dear Dr. Giménez,

NASA has received a description of the following mission, which has been identified as a mission that will be proposed to the European Space Agency (ESA) for consideration as a Cosmic Vision Medium-size mission (M4), as well as a description of the mission's science objectives.

Mission: Turbulent Heating ObserveR (THOR), Principal Investigator: Dr. Andris Vaivads, Swedish Institute of Space Physics, Uppsala, Sweden.

Letter requested by: Dr. Harald Kucharek, University of New Hampshire, USA.

NASA is aware of this proposal and acknowledges that its heliophysics objectives are aligned with the 2014 Science Plan for NASA's Science Mission Directorate (available at http://science.nasa.gov/about-us/science-strategy/).

This letter may be included in the proposal that is submitted to ESA. NASA has not provided ESA with a copy of this letter. NASA will enter into discussions with ESA about support of selected proposals at an appropriate time.

Sincerely,

Dr. Jeffrey Newmark
Interim Director, Heliophysics Division
Science Mission Directorate
NASA

NASA Participation?

- ✓ NASA Letter of 'Interest' submitted with original proposal
- ✓ Science Study Team (SST) is forming *now*.
  - ESA wants to see NASA interest to add US members
  - Funded Phase 0/A participation?
- ✓ Instrument/hardware proposals to 2016 Explorer AO?
  - ESA will *not* let an AO in Europe. It considers the instruments to be selected…


THOR